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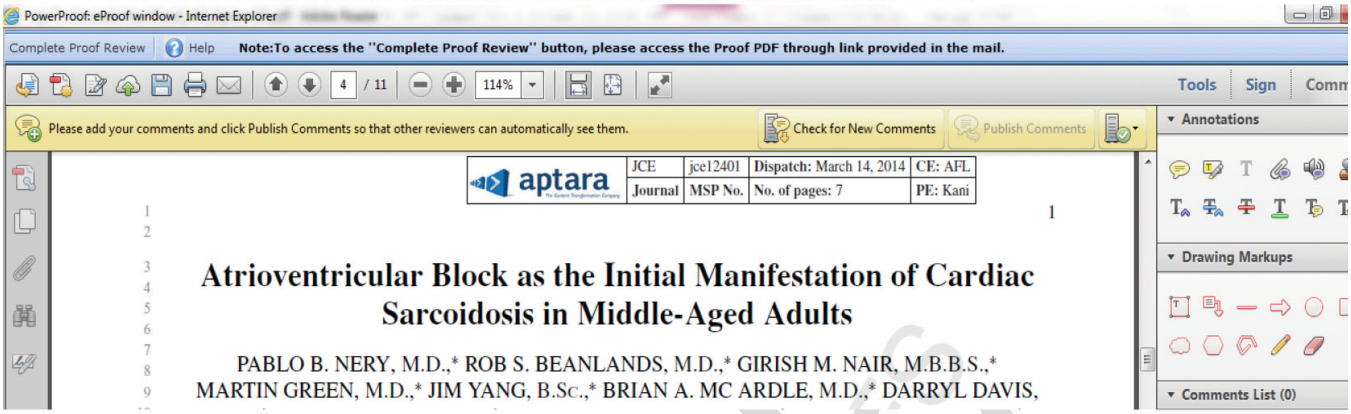

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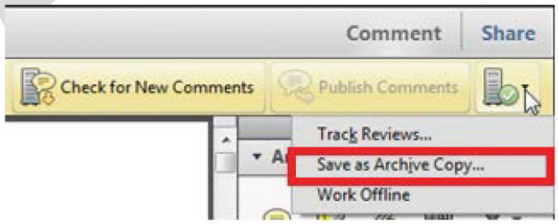

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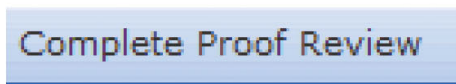

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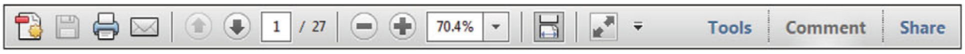

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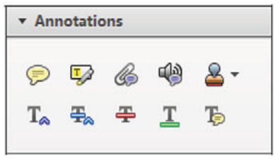

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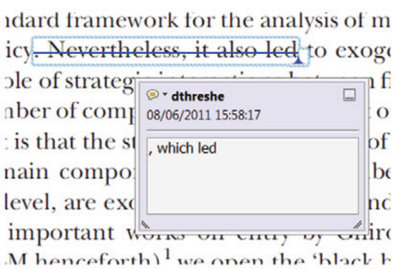

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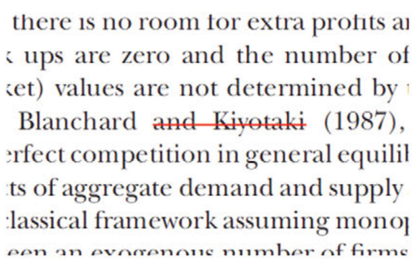

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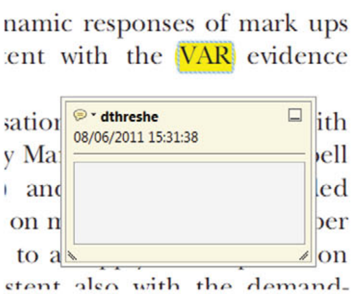

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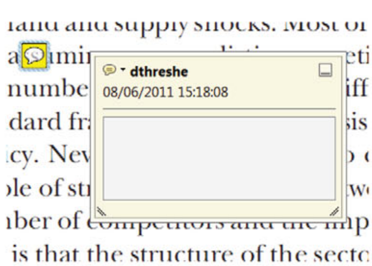

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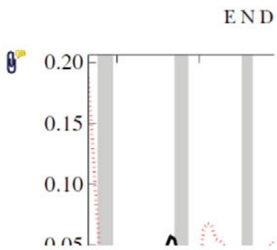

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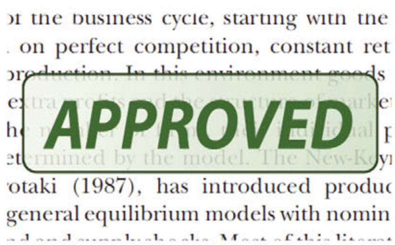

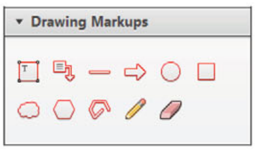

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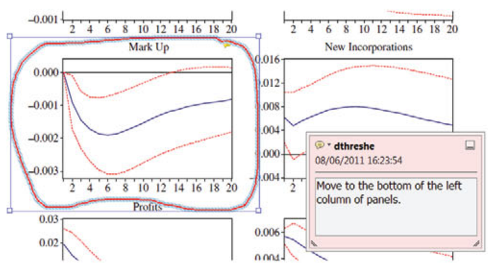

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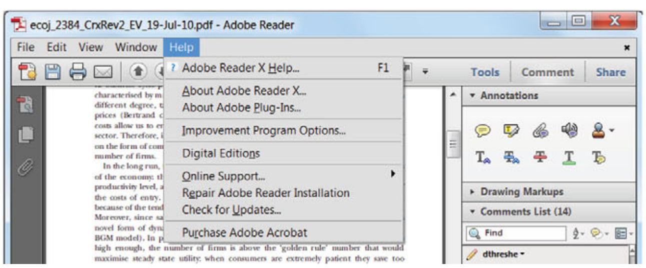

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RESEARCH ARTICLE

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Societal stability and environmental change: Examining the archaeology-soil erosion paradox

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Abstract

This paper critically examines the soil exhaustion and societal collapse hypothesis both theoretically and empirically. The persistence of civilizations, especially in the Mediterranean, despite intensive and presumably erosive arable farming creates what is described here as the archaeology-soil erosion paradox. This paper examines the data used to estimate past erosion and weathering rates~~,~~ before presenting case studies that engage with the theoretical arguments. Study 1 shows 5000 years of high slope erosion rates with both soil use and agriculture continuously maintained in the catchment. Study 2 shows how ancient agricultural terraces were constructed as part of an integrated agricultural system that fed the ancient city of Stymphalos—now abandoned. Study 3 presents a recent example of how after the removal of terraces high soil erosion rates result during intense rainstorms but that arable agriculture can still be maintained while external costs are borne by other parties. What these case studies have in common is the creation of soil, and increased weathering rates while productivity is maintained due to a combination of soft bedrocks and/or agricultural terraces. In societal terms this may not be sustainable but it does not necessarily lead to land abandonment or societal collapse.

KEYWORDS

agricultural terraces, mediterranean, societal collapse, soil erosion, sustainable resources

1 | INTRODUCTION

Soil lies at the base of all human subsistence systems and so it is unsurprising that it has been implicated in both archaeological and recent socioeconomic problems, particularly in regions with relatively low or unreliable rainfall and incomplete vegetation cover (McBratney, Fielda, & Koch, 2014). A narrative has emerged from environmental disciplines that soil erosion was implicated in the collapse or decline of past complex societies (Montgomery, 2007a). This paper questions this view through ~~examining~~ this degradation narrative and ~~presenting~~ three case studies which in different ways also question this narrative. The soil erosion driven societal collapse narrative can be interrogated through three propositions. The first proposition is that a soil exhaustion model may not adequately describe the soil mass balance over the medium timescale (10^2–10^3 years). The second is that past societies were aware of the danger and from earliest times employed techniques that manipulated the soil formation/erosion balance and in particular through agricultural terracing. The last proposition is that the abandonment of such soil conservation and creation measures is the most likely cause of short-term increases in soil erosion, loss of fertility, and soil profile truncation but that this can be compensated for by nutrient additions and external cost support. The three case studies exemplify these propositions with case study 1 being an example of continued arable agriculture despite extremely high erosion rates, while case study 2 describes a city-state where agricultural terracing was an integral part of the economy, and case study 3 illustrates the erosion rates and forms of erosion that can occur after the plowing-out of terraces on soft rocks. All the three examples discussed in this paper can be regarded as typically NW European or Mediterranean. The debate as to human impact on both erosion and soil production rates and the effects of agricultural terracing is a key element in the currently vibrant Anthropocene debate (Monastersky, 2015)

2 | THE RISE AND DECLINE OF AGRICULTURAL SOCIETIES, SOIL EXHAUSTION, AND SOIL CONSERVATION

Because soil has traditionally been viewed as a finite, or nonrenewable resource, several soil scientists, geomorphologists and biologists have considered soil, as not only a limiting factor for the growth of civilizations but also a possible cause of societal collapse through its overexploitation (Dale & Carter, 1955; Diamond, 2005; Mann et al., 2003; Montgomery, 2007a). As Montgomery (2007b) has remarked "The life expectancy of a civilization depends on the ratio of the initial soil thickness to the net rate at which it loses soil." So Montgomery (2007b) and others such as Chew (2001) have argued several civilizations collapsed for the primary reason that they destroyed their soil resources by arable cultivation above a sustainable rate, and so presumably suffered population collapse or out-migration due to increasing famine and food poverty. This narrative, also referred to as "overshoot" (*c.f.* Tainter, 2006), has been utilized in turn by soil scientists understandably critical of modern agronomy (Scholes and Scholes, 2013). However, archaeologists have failed to show convincingly a single example of this ~~scenario, indeed~~ further research has almost invariably led to a questioning of soil-based and other monocausal hypotheses (Hunt, 2007; McAnany and Yoffee, 2010; Tainter, 2006). Hence the title of this paper—the archaeology-soil erosion paradox, or how can societies continue despite what *would appear to be* unsustainable demands upon their soil base.

Montgomery's statement and the soil-collapse paradigm is based upon estimates of soil erosion under arable agriculture that appear to be several times greater, or even an order of magnitude greater, than soil production rates (Fig. 1; Montgomery, 2007b). For this to be the case, we have to be confident that both the estimates of soil erosion under the appropriate agricultural conditions and the soil production rates are realistic. In this regard, soil production is not easy to measure directly and so proxy measures are used. The most common is to assume soils are in equilibrium under natural conditions and use a natural or nonagricultural erosion rate to approximate the soil production rate. This gives low rates between 10^{-4} to 10^{-1} mm yr^{-1} that overlap with modern agricultural rates of 10^{-1}- to 10^{2} mm yr^{-1} (Montgomery, 2007b). An alternative that has only recently become available is to use an estimate of long-term soil erosion from cosmogenic radionuclides and particularly ^{10}Be and ^{26}Al on quartz (Small, Anderson, Hancock, & Finkel, 1999). An example is Heimsath, Chappell, Dietrich, Nishiizumi, and Finkel (1997); Heimsath, Dietrich, Nishiizumi, and Finkel (2000) who used ^{10}Be and ^{26}Al on greywacke in northern California, and on granites in south eastern Australia, making in both cases, the assumption that local soil thickness was constant with time. Also in Australia Wilkinson et al. (2005) estimated rates using ^{10}Be and ^{26}Al on Triassic sandstones in the Blue Mountains. Interestingly, the results in this case suggested to the authors that the soils were not in equilibrium probably because of a late Pleistocene glacial inheritance. These studies have produced estimates in the range 0.009–0.1 mm yr^{-1} (mean 0.1 mm yr^{-1}). In a much a much cooler climate estimates derived from the microweathering of roches moutonnées in Norway, are an order of magnitude lower (Andre, 2002). It is well known that cratons may have low weathering rates, but that in these areas deep soils have accumulated over hundreds of thousands of years.

A deeply embedded assumption in soil production theory is that there is an exponential or humped relationship between soil depth and the weathering rate (Carson & Kirkby, 1972; Cox, 1980; Heimsath et al., 2000). In both the humped or exponential curves the weathering rate falls to practically zero when soil thicknesses exceed 2–3 m Q2 and it is argued that this produces divergent evolution of soils with thin soils having a distinct contrast between bedrock and soil (clear and sharp weathering front) or thick soils with indistinct soil bedrock boundaries. However, there is evidence that soil-production functions (SPFs) are sensitive to root density and other ecological factors, many of which can extend many meters into the soil (e.g. due to termites) and cosmogenic data (^{10}Be) suggest soil chemical denudation rates increase proportionately with erosion rates (Fig. 1; Larsen et al., 2014). Given that increased porosity under bioturbation or tillage increases biological activity (respiration) and water movement, it should therefore increase the weathering rate particularly from increased hydrolysis of soil skeletal minerals. Most recently Johnson, Gloor, Kirkby, and Lloyd (2014) have estimated the depth dependency of soil bioturbation rates and shown that they are strongly related to rooting depth and also sensitive to the erosion rate. This process of soil formation can now be seen ~~due~~ to X-ray cross-sectional tomography scanning of tilled versus zero-tilled soils (Mangalassery et al., 2013). Q3 Therefore, soil production on soft rocks (e.g. loess or marls) is a function of the chemical weathering rate and bioturbation (including tillage) and this can allow the maintenance of a regolith, with fertility maintained by grazing and/or manuring (or chemical fertilizers today). On hard rocks, such as hard limestones, this cannot occur and soil thins and can be lost completely, although most will accumulate downstream in structural traps and floodplains. This causes the dichotomy often seen in Mediterranean regions with fertile soils in some areas and almost bare rock in others (Grove & Rackham, 2003). A good example of this dichotomy is the estimated soil erosion map of Crete as predicted by the G2 Erosion model (Fig. 2; European Soil Portal). This model estimates soil loss from sheet and rill erosion using a modified Universal Soil Loss Equation (USLE) on a monthly time step (Panagos, Karydas, Ballabio, & Gitas, 2013). Data input is from a number of European and Global databases for soils and digital elevation model data sets from satellites.

The slope weathering erosion system is further complicated by agricultural terracing. Agricultural terraces systems vary according to their morphology and means of construction but can be broadly grouped into slow and fast terraces (Grove & Rackham, 2003). Slow terraces are created behind walls, constructed along the contours and are associated with irrigation/drainage channels. Soil depth increases behind the walls through erosion upslope. In theory, these terraces can arise from walled co-axial field system or from stone clearance. Fast terraces or "bedrock"-cut terraces have risers cut into slope creating new saprolite behind terrace wall. Both slow and fast terraces increase the total saprolite and ~~so could~~ increase effective weathering rate especially under tillage, as discussed later in this paper. In parts of Europe such as the UK and northern France terraces were constructed directly from soils and weathered saprolite, especially on soft limestone (chalk), often without walls and these are referred to as lynchets (Chartin, Bourennane, Salvador-Blanes, Hinschberger, & Macabre, 2011; Lewis, 2012). In the Mediterranean, terracing has been regarded as a key element in the erosional history of as determined from colluvial and alluvial chronologies (Grove & Rackham, 2003; Van Andel, Runnels, & Pope, 1986; Van Andel, Zangger, & Demitrack, 1990).

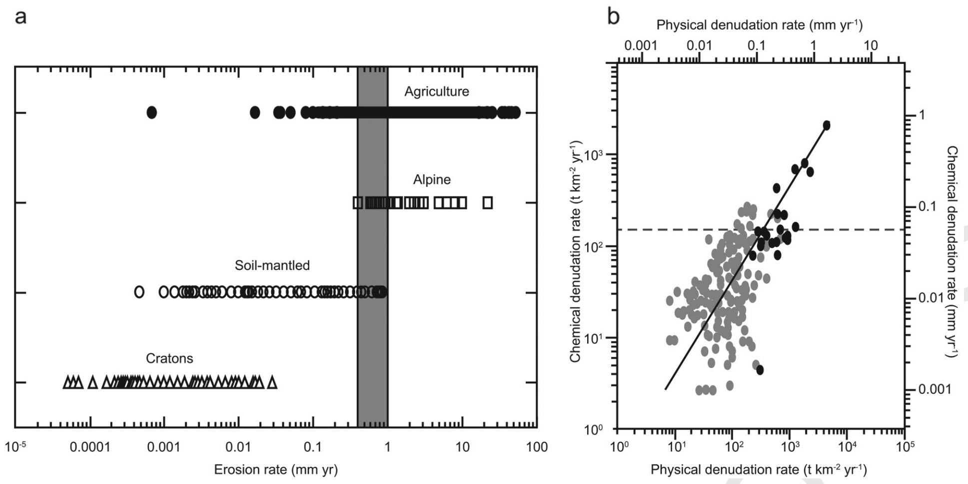

FIGURE 1 (a) Plot of erosion rates from Montgomery (2007b). (b) Physical versus chemical denudation rate from Larsen et al (2014)

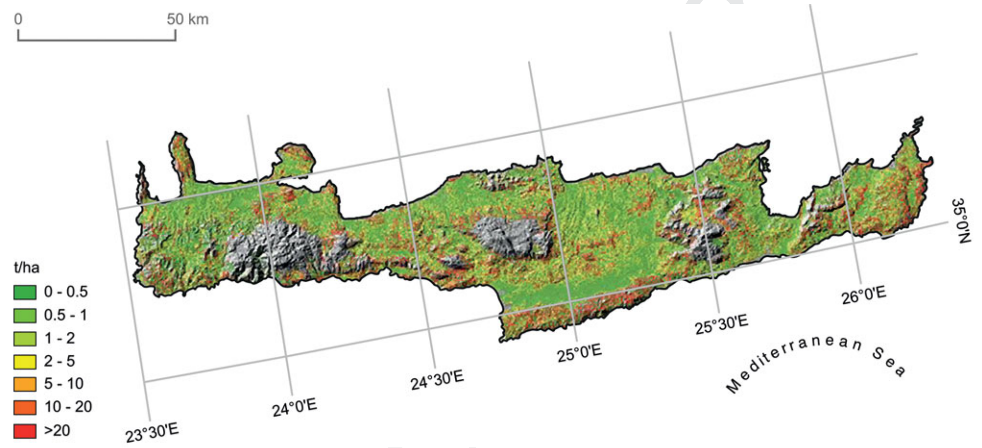

FIGURE 2 G2 Erosion model for Crete from the European Soil Portal. ©European Union, 1995–2015

3 | CASE STUDY 1: THE FROME CATCHMENT UK

The erosion and societal collapse literature tends to focus on Mediterranean or semi-arid ~~environments, however,~~ very high erosion rates may also be observed in the cool temperate zone of North West Europe. This is particularly true with catchments with relatively moderate rainfall and on soft sedimentary lithologies such as the river Frome in the Midland region of the UK. The Frome is a small (144 km^2) low relief catchment entirely on soft and friable mudstones in the West Midlands of the UK (Fig. 3). These lithologies produce argillic brown earths soils that are moderately to highly erodible but inherently fertile (Fig. 3). The catchment receives moderate annual precipitation (706 mm yr^{-1}) that can exceed annual potential evapotranspiration although there can be a small moisture deficit (400-200 mm) during the summer and this has led to field irrigation in modern times. Pollen analyses from the alluvial valley indicates that the catchment was almost entirely deforested by the late Bronze Age (*c.* 3000 cal. yr B.P.) and under arable cultivation with much of the resulting eroded soil being deposited as overbank alluvium along the valley floor (Brown, Dinnin, & Carey, 2011; Brown, Toms, Carey, & Rhodes, 2013). Using seven cross-sections of the valley and both radiocarbon and optically stimulated luminescence (OSL) dating, estimates were made of the deposition rate of sediments in five of these reaches (Fig. 4). Since it is reasonable to assume a constant delivery ratio over such a small change in catchment area (77–144 km^2) these rates can be converted into minimum erosion estimates (Fig. 4). These rates vary from 40 to 100 t km^2 and show a distinct increase over the last 5000 years. These rates are also comparable to another small catchment 28 km to the southwest, which was the first location in which this type of budget analysis was attempted in the UK (Brown & Barber, 1985). The resultant over-thickened and homogenous superficial floodplain sediment unit is found over wide areas of the English Midlands and was first recognized in the 1970s by Shotton who termed it the buff-red silty clay (Brown, 1997; Shotton, 1978). Due in part to its known high erosion rates, the catchment sediment discharge of the Frome has been measured within the last decade (Walling, Collins, & Stroud, 2008) and from these studies we know that the recent (2000–2004) estimated erosion rate is 19.4 t km^{-2} year^{-1}. Due to the incised nature of the channel today, the contemporary sediment loads are derived from bank erosion (estimated at 48%), cultivation (estimated at 38%), and pasture (estimated at 16%; Walling et al., 2008). Given these rates and the volumes

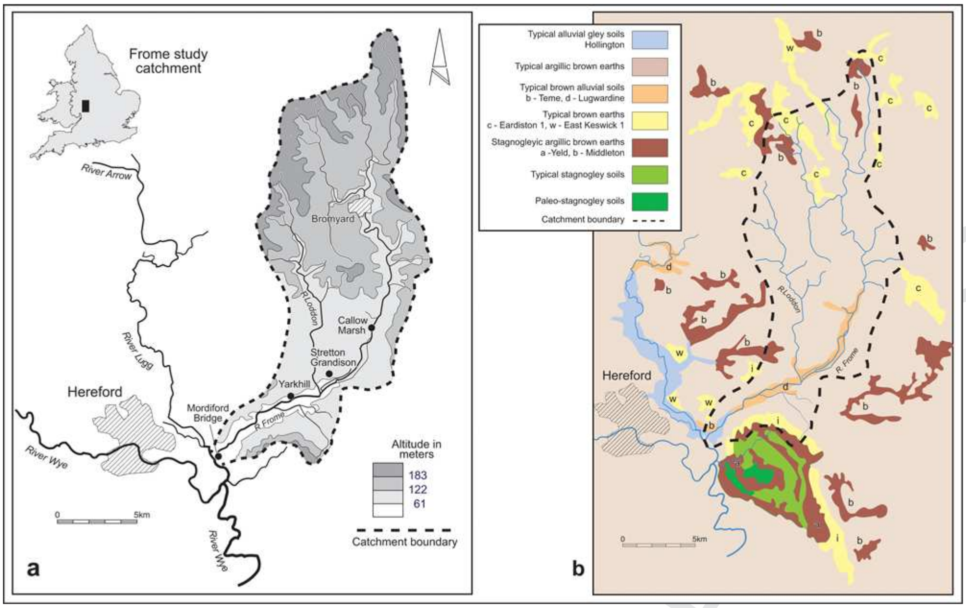

FIGURE 3 Map of the Frome catchment UK (a) topography and (b) soils

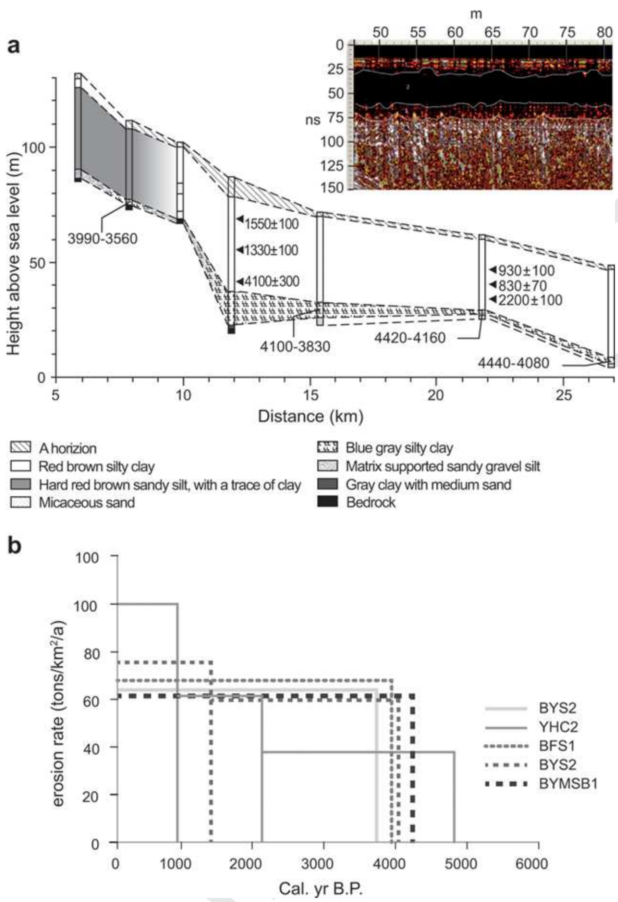

FIGURE 4 Sedimentary data from the Frome catchment. (a) Stratigraphic long section of the valley with radiocarbon and OSL dates and inset of GPR cross-section at Stratton Grandison, (b) estimated minimum erosion rates from the River Frome, West Midlands, UK derived from ^{14}C and OSL dates cross-sections and the catchment area of each cross-section. Diagram new and adapted by authors from Brown et al. (2013) with additional data

of sediment stored in the floodplain it would take *ca*. 60,000 years to remove all the stored sediment at the present erosion rate.

Despite this high erosion rate the catchment is still covered in relatively deep soils (argillic brown-earths) and has a dense multi-period archaeological record (White & Ray, 2011). There are still remnants of lynchets on some slopes but it is not known precisely what age they are. Other archaeology includes abundant evidence of arable agriculture and settlement in the late Prehistoric and Roman periods and a rich record of Medieval settlement (White & Ray, 2011). A good example of this is the area around Venn Farm, Bishops Frome, which is located in the middle of the valley just to the south of Bromyard (Fig. 3) which revealed Medieval kilns (probably for corn drying), ridge and furrow (arable strip cultivation), a mill, mill race, and an associated agricultural earthwork terrace (Hoverd and Roseff, 1999). In the 19th century Q4 it developed an intensive hop (for brewing) and soft fruit agriculture. Data have been extracted at a parish level from the Post Office Directory of Hertfordshire (1851–1931) and other trade directories in order to document rural population change from 1853 to 1931 as part of the Frome Valley Project (Table 1). This shows that maximum population densities occurred in the mid to late 19th and very early 20th centuries supported by the intensive cultivation of hops, wheat, barley, apples, and fruit. At the peak these rural population densities reached remarkably high values (0.9 persons ha^{-1}) that would today be regarded as unsustainable (Rose, 1996), however, this was achieved through the intensive arable cultivation of fields and lynchets that had been agricultural soils for over 3000 thousand years. The catchment remains predominantly under intensive arable cultivation today (largely cereals) and as has happened over much of the UK field size has increased (White & Ray, 2011). Fertility is maintained by both the addition of farmyard manure and also chemical (NPK) fertilizers. However, one negative aspect of this high erosion rate has been the almost total removal of archaeological features including terracing, from the catchment slopes and also the burial of significant archaeology within the

TABLE 1 Population and land values for parishes in the Frome Valley in the mid-19th century. Data from The Frome Valley Project. Data extracted by B. E. Haner

Parish	1861 Population	Peak Population (date)	Parish Acreage	Rateable Value in 1861 £	Pop. Density in 1861 Persons km^2
Ashperton	534	(1861)	1715	2839	76.9
Avenbury	371	391 (4871)	3048	3982 (4871)	30.0
Bishops Frome	50	(1891)	3950	905	3.1
Bredenbury	52	119 (1901)	555	1023 (1881)	23.2
Canons Frome	115	254 (1911)	1005	1504	28.3
Edwin Ralph	165	163 (1881)	1590	1695	25.6
Linton	547	616 (1881)	2430	3759	18.1
Much Cowerne	563	(1861)	3535	5214	39.3
Norton	623	(1861)	1708	4407	90.1
Stanford Bishop	234	235 (1851)	1471	1829	39.3
Thornbury	224	241 (1871)	2130	2426	26.0
Wacton	123	129 (1851)	1002	976 (1881)	30.3
Winslow	440	491 (1851)	3106	4337	34.9

floodplain (Brown et al., 2011). However, the eroded soil also significantly increased the alluvial area in the catchment and this has been exploited by both arable cultivation (including potatoes) even in areas “liable to flooding” and also by highly productive pastoral agriculture. This included at Paunton Mill the construction of an integrated corn mill and water meadows constructed on an area of post Bronze Age alluviation (Hoverd & Roseff, 1999).

4 | CASE STUDY 2: TERRACES IN THE STYMFALIA VALLEY NW PELOPONESE, GREECE

The geological context for soil erosion in the Mediterranean is most commonly limestone mountain massifs, structural basins, and human exploitation of hydrogeology. The Stymfalia Valley is a polje (structural valley in limestone) in the NW Peloponese in Greece. It was the location of the classical city of Stymphalos from 700 to 375 B.C. and again from 375 B.C. to 6th century A.D. (the Late Classical City), after which it fell into decline. Stymphalos is famous in classical mythology as the location of Hercules sixth labor—the killing of the Stymphalian birds. The site of the classical city is surrounded by a reed-fringed lake that is less than 2 m deep and has been known to have dried out in historical times. Being a polje the hydrogeology of the valley is complicated, but in essence valley-side springs on the north face of the valley under Mt. Kylini supply water to the valley floor and lake. The lake has a natural outlet on its southern side that is a sink-hole. Sink-holes are prone to ~~get plugged up or sealed~~ by sediment and can therefore “behave” erratically and this is clearly the source of stories told in antiquity of the sudden drainage of the lake as recorded by the Classical writer and geographer Pausanias (Clendenon, 2010). The Hercules myth is also probably related to the erratic behavior of the lake in an indirect fashion as well as the Greek myths of the hunter-gatherer origins of the Arcadians in their brutish environment (Schama, 1995). However, the valley-side springs were essential for water supply to agricultural terraces up to an altitude of 900 m above sea level. These springs also supplied water to the valley-base alluvial fans that formed local aquifers closer to the ancient city and under the modern village of Stymfalia. Although the agricultural terraces have yet to be independently dates, erosion at Bouzi revealed a buried landsurface covered by 0.4 m of soil that contained an assemblage of Roman pottery. This terrace system is developed below the springs at upper village of Stymfalia and it includes a series of water channels designed to feed water from the spring onto the terraces (Fig. 5).

Coring in the valley floor and through the lake by Heymann et al. (2013) and Walsh, Brown, Gourley, and Scaife (in press) has allowed the creation of a sediment deposition model. Sedimentation has also been investigated by coring close to the edge of the city where over 2 m of marginal lake sediment has been shown to contain pottery and brick from the city (~~Walsh et al., in press~~). Both the central and marginal cores reveal that the maximum accumulation rates post-date the Classical period: at *ca.* 2000–1200 cal. yr B.P. and there is no evidence that the preceding 700 years of city occupation was associated with atypically high deposition rates in the lake. Since the valley has no significant sediment contributing areas other than the immediate slopes around Stymphalos and the valley has no outlet other than the sink-hole the rates of deposition can be taken as a proxy for the erosion rate. The fountain House cores suggest an average accumulation rate of 1.7 mm yr^{-1} and the core published by Heymann et al. (2013) shows an increase in the accumulation rate further out into the lake from 0.56 mm yr^{-1} to 1.3 mm yr^{-1} in the early Classical Period to around 0.36 mm yr^{-1} subsequently. Using both estimates from the Fountain House cores and the core by Heymann et al. (2013) the estimated accumulation rates if averaged over the lake basin area (from Papastergiadou, Retalus, Kalliris, & Georgiadis, 2007) would produce a long-term average clastic erosion rate in the catchment of approximately 0.1 to 0.04 t ha^{-1} yr^{-1}. It is not surprising that these rates are low, although higher than the Holocene average that is approximately 0.01 t ha^{-1} yr^{-1} as all

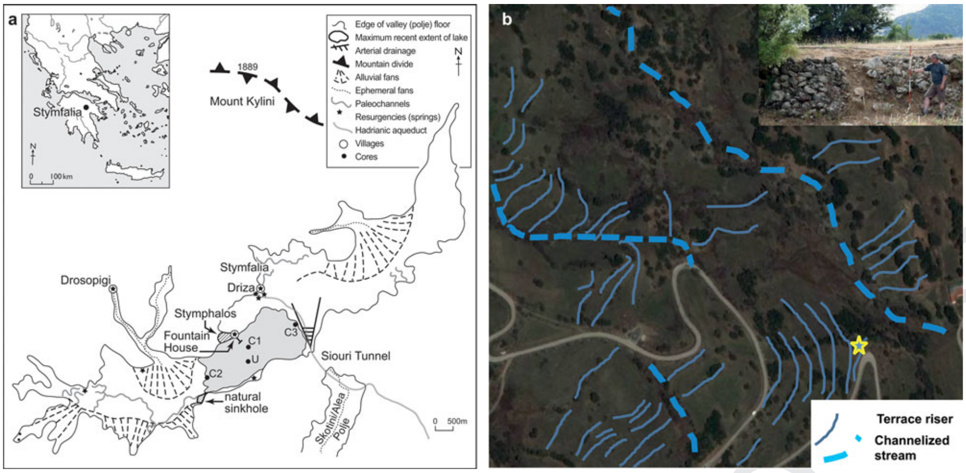

FIGURE 5 The Stymphalos polje with the alluvial fans, springs, core locations (a), and the location of the Bouzi terrace system (b)

the bedrock in the catchment is relatively pure limestone and so would be expected to dominate the total denudation loss but at a rate linearly related to precipitation (Simms, 2004). Although the dating needs to be improved, it is likely that the higher erosion rates post-date the abandonment of the city that was caused fundamentally by a political shift of power to the Corinth area facilitated, at least in part, by the water supply taken from the Stymphalos valley-lake. The importance of Stymphalos as a source of water was transformed during the Roman period when the Hadrianic aqueduct to supply water for Corinth was built. The manipulation of this plentiful water supply, more specifically the spring at Driza, just to the north of Lake Stymphalos (Lolos, 1997) by Roman technology altered the very nature and meaning of water at Stymphalos. This does not mean to say that local people's engagement with the lake and surrounding springs, and the springs' associations with sanctuaries and deities necessarily changed. However, the capture of this source must have affected inputs into the lake and at least part of the hydrological system around Stymphalos. Such a structure not only creates a physical link between the source and consumer of the water (in this instance Corinth), but it also may have changed the nature of cultural and ideological links between the source area and the consuming city symbolic of the loss of autonomy of the city under Roman rule. This change in a community's or society's relationship with water would have course been true in any landscape where such a feat of hydraulic engineering had been undertaken. In Greece alone there were *ca*. 25 aqueducts plus a dozen across the Greek islands (Lolos, 1997). This example shows the importance of hydrogeological resources in the location and management of terraced slopes but also the difficulty in quantifying the effects of such management on erosion and sediment loss in a polje basin.

5 | CASE STUDY 3: RECENT TERRACE LOSS AND EROSION IN SW SPAIN

Observations over a number of years in the Ardales area, Malaga Province, SW Spain have revealed the consequences of land use change on the nature and pattern of soil erosion (Fig. 6). Geologically, the area is part of the Betic Cordillera that forms a spine of limestone mountains flanked by Oligocene marls and Miocene conglomerates (Fontbote et al., 1970). The marls form areas of undulating relief within structural basins and they vary in colors from red through pink, white gray/green to light brown. The area also exhibits incipient badland formation on the steeper slopes. The area has a typical Mediterranean climate with a pronounced summer moisture deficit of 600–800 mm yr^{-1} (Mairota, Thornes, & Geeson, 1998). The study area is centered on a large field 10.5 ha in size comprising a large north facing slope of approximately 100 m relative relief and steeper south facing slope on which the badlands have formed (Fig. 7). The field has been ploughed out of an area of smaller fields and matorral-type vegetation and on the steep north facing slope several abandoned agricultural terraces were also plowed-out in the 1980s. This was despite a slope of over 30° and was only possible due to the adoption of small caterpillar-tracked tractors. The field was monitored from 1987 to 1994 using a variety of techniques designed to indicate soil thickness and condition. These included soil bulk density, penetration resistance, electrical resistivity, field radiometry, and the use of the airborne thematic mapper (ATM), which is a hyperspectral scanner mounted in a light aircraft (Brown, Schneider, Rice, & Milton, 1990). The principal laboratory analyses of the soils were the determination of organic matter using both loss on ignition and wet oxidation, and $CaCO_3$ content using a Collins calcimeter that has a standard maximum error of 2%. The soils in the field all had low levels of organic matter ranging from 0.5 to 0.9%.

In order to get a complete view of the entire study area airborne remote sensing was used. So on 16th May 1989 the a Piper Chieftain flew over the area deploying a Daedalus multispectral scanner. The field was partially covered by an emerging seedling crop of chick-peas and the soil was dry. The data were transferred to the Erdas image processing system, cleaned and geometrically corrected using ground control points from stereo aerial photography. Although only approximate this method did remove along-flight stretching. The removal of atmospheric effects was achieved using dark object subtraction and off-nadir view angle/path length effects were assessed by plotting the mean digital number for every 5 pixels across the flight-line and although there was some evidence of a trend it was much reduced for the longer wavelength bands. The hyperspectral scanner

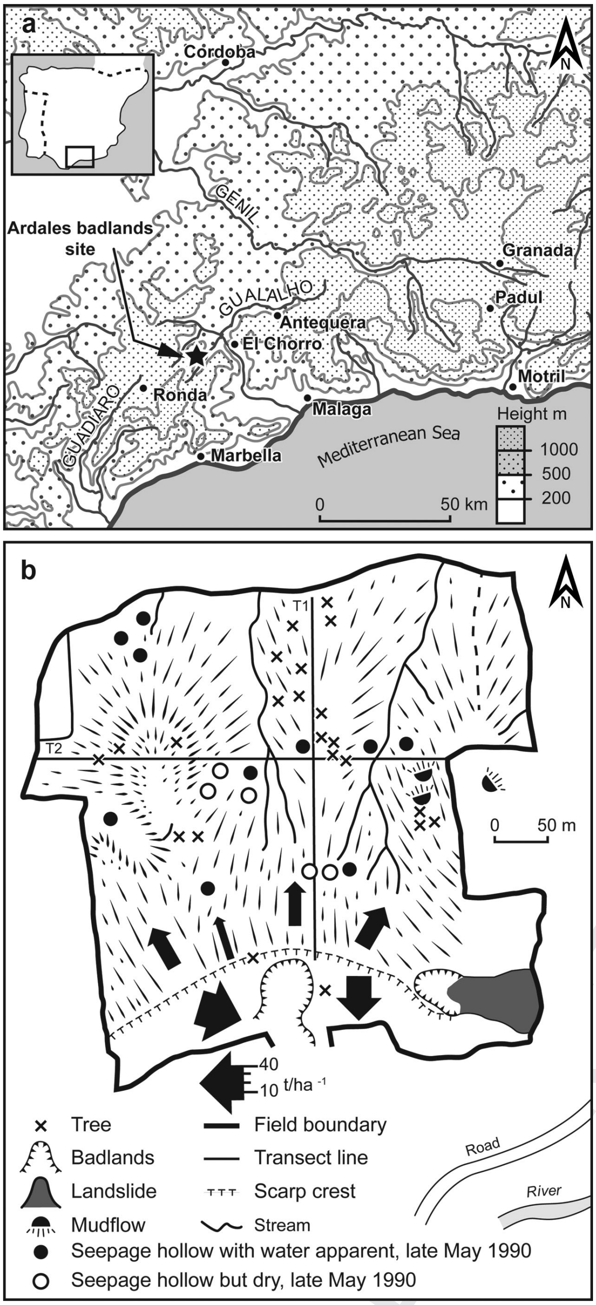

FIGURE 6 Location maps and soil erosion data from the Ardales soil erosion study area after the November 1989 event

reflectance data were used in an attempt to estimate soil quality and depth through soil surface properties and specifically topsoil $CaCO_3$ content.

On noncultivated soils a soil truncation model developed by Brown et al. (1990) can be used to estimate soil depth, and on the carbonate-rich marls this can be estimated from surface carbonate content. Field studies using a Milton Multiband radiometer on two successive years had shown that the principal determinant of bare-soil variation in the field was total carbonate content. The correlation was strong and statistically significant in all bands (blue, green, red, NIR) but highest in red. A regression equation between $CaCO_3$ content (25–70%) and red reflectance was also produced using a spectroradiometer (SIRIS) and this was then used to generate a pattern of soil carbonate content variation across the field from the ATM data. Although the carbonate content had a clear relationship to topography estimates of soil depth using soil resistivity showed it to be only partially related to topography (Fig. 8). The confounding factor appeared to be lithological variation with a band of a band of calcareous sandstone separating clastic limestones in the west from fossiliferous limestones and further sandstone in the east. The resistivity data was inversely modeled and the model tested using coring. Where there was a sharp boundary to soil depth there was agreement with the model and where it was gradational the boundary was defined as the inflection of the resistivity curve (Payne, Brown, & Brock, 1994). Soil depth varied from 3.3 m in spurs to 0.1 m on the highest spur. Erosion modeling using a simple cost surface (D. sin θ), the Pert Amboy model, Western Colorado model and Meyer and Wischmeier models had weak statistical relationships to the resistivity model but did exhibit lowest values on the lowest slopes of the interfluves (Payne et al., 1994). The topography was also found to be closely related to seedling emergence of both chick peas in 1990 (Brown et al., 1990) and density of barley in the summer of 1992 (Payne et al., 1994).

As can be seen in Figure 7 the hill had been converted into a single very large field sometime before the 1980s and this had removed two and maybe three small agricultural terraces on the steep south-facing side of the interfluve and morphologically typical badlands had started to form at the western end of this slope. In November 1989, a major storm hit the area with rainfall intensities reaching 25 mm h^{-1} for an hour long storm (Tout, 1991) and this event caused extensive rilling and gullying over the entire area. A survey of these rills and gullies allowed estimates to be made of the event-related soil erosion rate. On the steepest south facing slope this rate was as high at 40 t ha^{-1} (equivalent to 0.40 t km^{-2}). Eroded soil and even large stones from the field (some probably old terrace walling) covered the local road (Fig. 7c). However, within a few weeks this was cleared and all the slopes replowed using a caterpillar tracked plow and, just as in case study 1, these slopes remain in arable production today despite what would appear to be an unsustainable long-term erosion rate due fundamentally to the geotechnical properties of the marl bedrock.

It is not easy to relate these modern quantitative estimates to ancient soil erosion history in southern Spain due to a lack of quantification in the archaeological studies. However, studies by Wise, Thornes, and Gilman (1982) and Gilman and Thorne (1985) showed that badlands can be of geological origin and more recent studies have shown that erosion rate can be higher on agricultural land in surrounding badlands areas (Mairota et al., 1998; Wainwright and Thornes, 2004). Longer records are possible from fluvial sediments and studies on several basins in south eastern Spain summarized by Schulte (2002) show a correlated increase in fluvial activity Early Medieval Ice advance (6th–10th centuries A.D.) and the Little Ice Age (15th–19th centuries A.D.) and lower activity in Medieval Climatic Optimum (Medieval Warm Period). Archaeological studies on seven sites in southern Spain have shown a degree of continuity between Roman and the Islamic period irrigated agriculture including terrace systems such as those at Benialí, in the municipality of Ahín (Butzer, Juan, Mateu, Butzer, & Kraus, 1985).

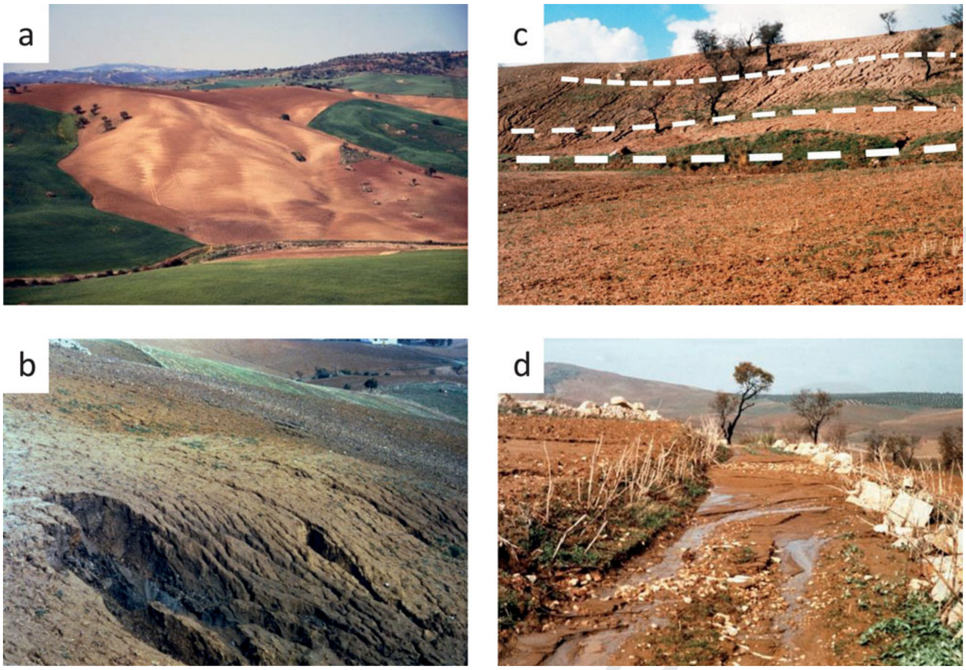

FIGURE 7 Photos of the Ardales soil erosion study Area after the major event in November 1989, (a) north facing slope having been plowed, (b) the south facing slope adjacent to the incipient badland formation with old terraces indicated by broken white lines, (c) rilling and soil slipping on the north facing slope, (d) the public road at the base of the north-facing slope after the 1989 event. See text for discussion of this map

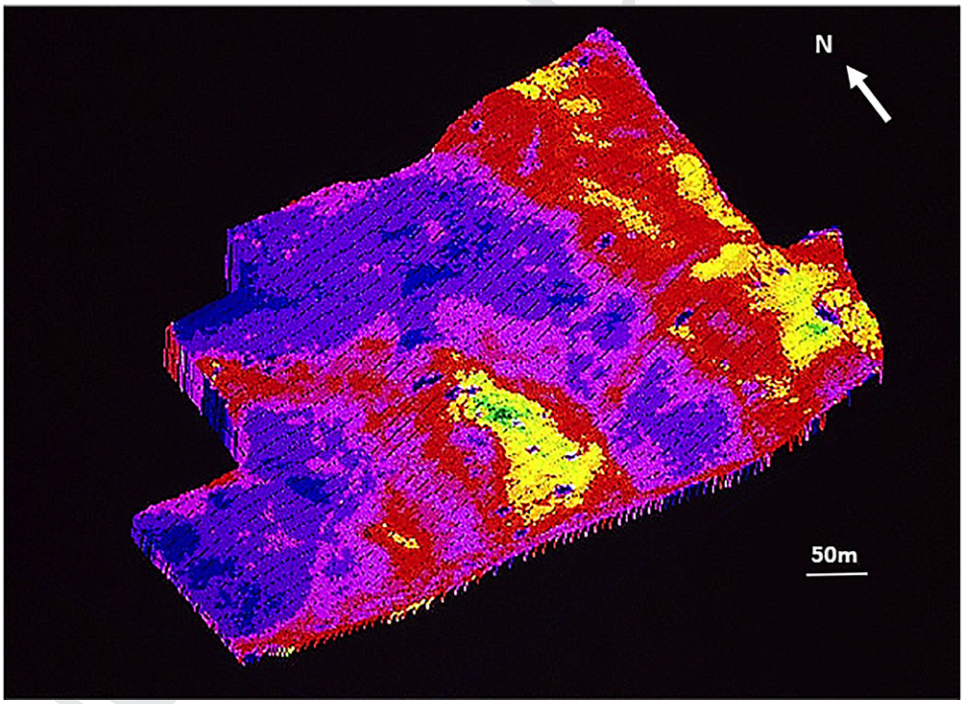

FIGURE 8 A false color map of estimated soil calcium carbonate values over the Ardales soil erosion study area derived from a transformation of multispectral scanner data flown on 15th of May 1989. The scaling is from green/yellow (<0.1 m) to dark-blue (>1 m) as validated by coring and penetrometry Q6

6 | DISCUSSION

Evidence from chemical denudation and theoretical considerations suggest that the soil production rate is not independent of the erosion rate and there is therefore a negative feedback on soil loss, especially on soft lithologies. Soil production rates are difficult to measure directly, however, new techniques being applied to this critical zone such as grain history using OSL or burial dating using cosmogenic nuclides do offer the potential in this respect (Davidovich, Porat, Gadot, Avni, & Lipschits, 2012; Gadot et al., 2016). In each of these case

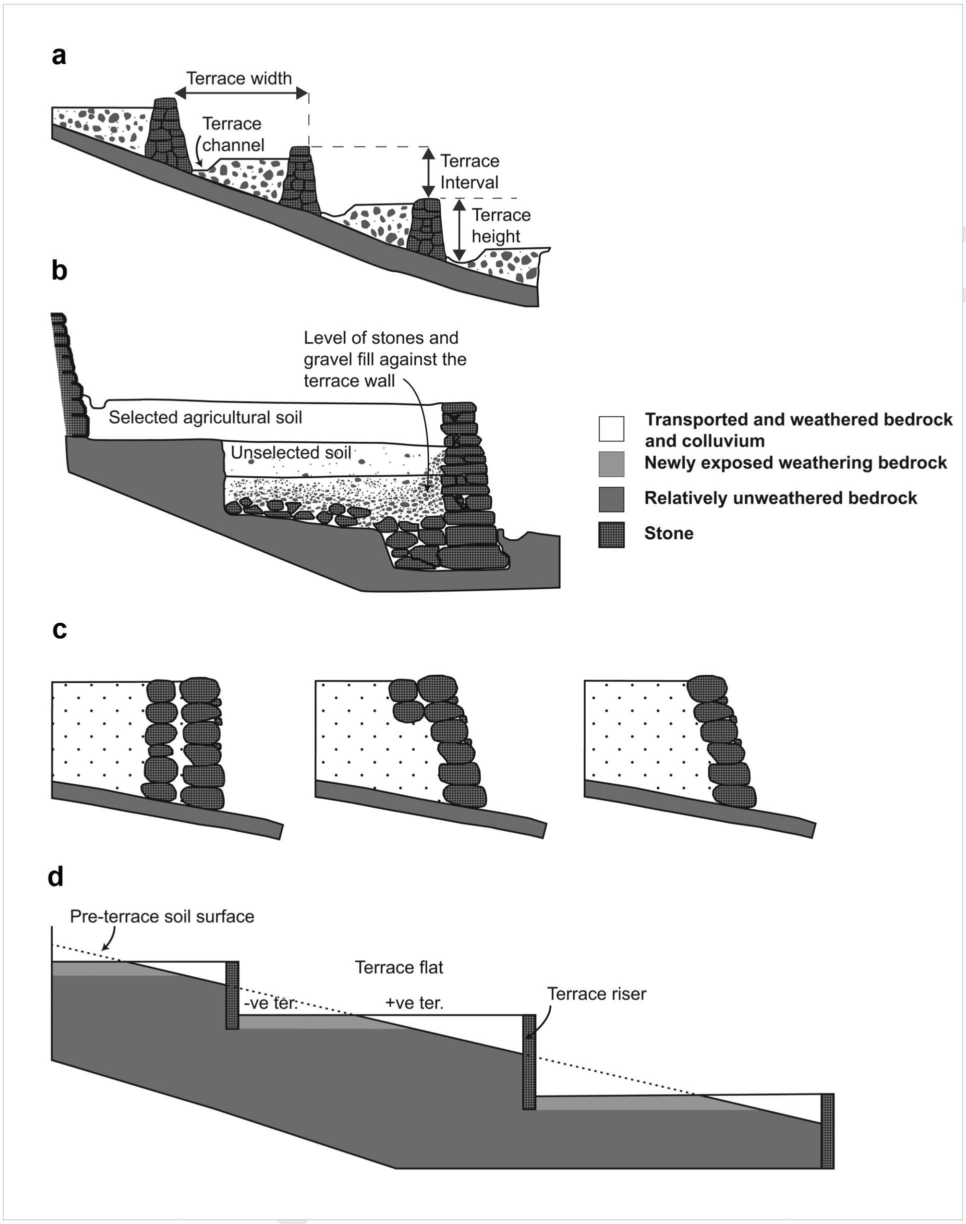

FIGURE 9 Agricultural terraces (a) terrace terminology, (b) Inca terraces adapted from The Cusichaca Trust, (c) Levant terracing types from Davidovich et al. (2012), and (d) terrace with soil formation and bedrock weathering zones

studies soil erosion is either socially accepted and adapted to, and/or managed by agricultural terracing and there is evidence from a few locations that this was part of a deliberate attempt to reduce erosion, maintain fertility, and thicken soils. Although now largely plowed-out, terraces in the form of lynchets were probably common in the Frome catchment in the past as they were across much of the UK (Curwen, 1939). In a study of terraces in the Cheviot Hills in Northern Britain Frodsham and Waddington (2004) have shown that some of these lynched-type terraces could be of late Neolithic or early Bronze age date.

Nearly all complex societies, and indeed many less politically complex societies such as in the American Southwest (Doolittle, 2000), used extensively, or even relied upon agricultural terracing. Within Western Europe and the Mediterranean agricultural terraces date back several thousand years and are one of the hallmarks of complex societies (Bevan & Conolly, 2011; Broodbank, 2013; Davidovich, et al., 2012; Grove & Rackham, 2003; Walsh, 2013:). Archaeological or historical terraces are generally of the bench (or fast) type with stone walls (Fig. 9) that require maintenance—typically 600–1200 days work per hectare (FAO, 2013). Agricultural terraces have generally been underresearched by geomorphologists due to their scale—too small to be represented on topographic maps. However, the advent of laser altimetry (LIDAR) is now allowing rapid mapping and process modeling (Tarolli, 2014; Tarolli, Preti, & Romano, 2014).

There has, however, been considerable experimental research on the effect of terraces on soil erosion by soil conservation services and related institutions (e.g. AAFC, 1999; FAO, 2000; FFTC, 2004; GPA, 2004; USDA, 1980) who all agree that terracing reduces runoff

TABLE 2 Estimates of soil erosion reduction resultant upon agricultural terracing

Location	Practices, Slope, and Other Measures	Erosion Reduction	Reference
Paraná, Brazil		~50%	IAPAR, 1984
	Also grassed waterways & contour plowing	Over 95% (20 tons ha^{-1} to under 1 tons ha^{-1})	Chow, Rees, and Daigle (1999)
Malaysia	35°, peppers	96% (63 t ha^{-1} yr^{-1} to 1.4 t ha^{-1} yr^{-1})	Hatch (1981)
Missouri River Valley, USA	Contour plowing	800% reduction	Schuman, Spurner, and Piest (1973)
Western Japan	Tree planting	Continuous decline for 35 years	Mizuyama, Uchida, and Kimoto (1999)

and soil erosion generally to very low levels if not zero (Dorren & Ray, 2012 Table 2). In many instances, it is the combination of terracing and maintaining vegetation cover that reduced soil erosion and increased soil erosion after terraces abandonment in the Mediterranean area in Spain results from a reduction in vegetation cover (Inbar & Llerena, 2000). Inbar and Llerena (2000) conclude that one of the key erosion reducing activities is the maintenance of the terrace walls. Terrace abandonment has been shown to cause massive soil loss (Cerda-Bolinches; 1994; Harden, 1996; Vogel, 1988). In a study of soil erosion before and after terrace abandonment Koulouri and Giourga (2007) showed that on typical slopes (25%) soil erosion increased post abandonment due to the replacement of herbaceous ground cover by shrubs and this lead to the partial collapse of dry-stone walling. So poorly designed or maintained terraces can cause significant soil erosion as shown by Van Andel et al. (1986, 1990) while well designed and maintained systems reduce soil erosion rates even with high population densities (Wilkinson, 1999) but are unsustainable under conditions of rural depopulation (Douglas, Critchley, & Park, 1996). Terrace abandonment is a particular feature of islands in the Mediterranean in the 19th–20th centuries (Allen, 2009; Petanidou, Kizos, & Soulakellis, 2008).

There have been a number of geoarchaeological and landscape archaeology studies of terraced landscapes such as on Antikythera (Bevan & Conolly, 2011; Bevan, Conolly, & Tsaravopoulos, 2008), the Kythera Island Project (Krahtopoulou & Frederick, 2008), on the island of Ikaria (Tsermegas, Dłużewski, & Biejat, 2011), at Markiani, Amorgos, in Greece (French & Whitelaw, 1999), and in the American Southwest (Sullivan, 2000) ~~that~~ show multiple phases of terrace use and construction, suggest variable effects on soil erosion, and in the case of the American Southwest at least sociopolitical rather than ecological reasons for terrace abandonment. But in a rare archaeological and historical study of a terraced landscape at Aáin, southern Spain, Butzer (1990, 2011) found no discernible soil erosion over a period of 400 years. These studies suggest terraces are both efficient and resilient during the Medieval and into the post-Medieval periods but can fail due to abandonment when under environmental or severe social stress. Other studies of small catchments that have estimated both long-term soil erosion and sediment retention have shown that colluviation (soil storage on slopes) can be beneficial rather than detrimental as it is more suited to intensive cultivation (Houben, 2012; Houben, Schmidt, Mauz, Stobbe, & Lang, 2012). This means that once constructed the life-history of terraces (*sensu* Dennell, 1982) both documents social history, in particular rural population densities, and drives soil erosion and land degradation (Blaikie & Brookfield, 1987). This is probably one of the principal causes of non-linearity in the relationship between population density and soil erosion. So the history of terraces is important in the archaeological soil erosion debate since they clearly indicate a concern at multiple levels in society to conserve soil and water in the face of a fluctuating environment as proposed by Van Andel et al. (1986, 1990), although it is often still not clear whether they were constructed due to high population pressure, climate change or facilitated population growth. In the other two case studies agricultural terracing had formed an important element in the management of the environment. This debate also has contemporary significance as at present they are being destroyed at a remarkable rate (FAO, 2013), form a significant element in soil security (McBratney et al., 2014) and are a vanishing part of our cultural heritage, particularly in European landscapes.

7 | CONCLUSIONS

The Mediterranean in particular has been the scene of a polarized debate (*cf*. Attenborough, 1987; Grove & Rackham, 2003) between those believing it is in essence a degraded environment, which illustrates how inappropriate and overintensive agriculture in a climatically marginal environment is not sustainable and has led to societal collapse (Montgomery, 2007a,b) as opposed to a view that sound ecological behavior and transgenerational continuity has been typical of most Mediterranean complex societies (Butzer, 2005; 2011). This paper has presented both theoretical arguments and some empirical data that supports four propositions in relation to the nature and severity of human-induced erosion in the past. First, the simple application of soil exhaustion models is likely to be misleading on soft lithologies where soil production is a function of tillage and can be modified by agricultural terracing. Terracing, which was probably designed to maximize water retention and ease of cultivation, is an almost universal adaptation in complex agricultural systems due to its widespread utility and sustainability. However, terrace abandonment that implies a reduction of population to below the local carrying capacity (i.e., due to other causes) will result in terrace-wall collapse and terrace failures that are known to increase the soil erosion rate. Finally, it is suggested that agricultural terraces added resilience to classical agricultural systems and could remain sustainable in agricultural systems today, given the right economic or other incentives.

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